

Low-Cost Large Aperture Telescopes for Optical Communications

H. Hemmati

*Jet Propulsion Laboratory
California Institute of Technology*

August 15, 2006

Background:

- Low-cost 0.5-1 meter ground apertures are required for near-Earth laser-communications
- Low-cost ground apertures with equivalent diameter ≥ 10 -m are desired for deep-space communications

Objective:

- Identify schemes to lower the cost of constructing networks of large apertures
 - Meeting the requirements for laser-communications

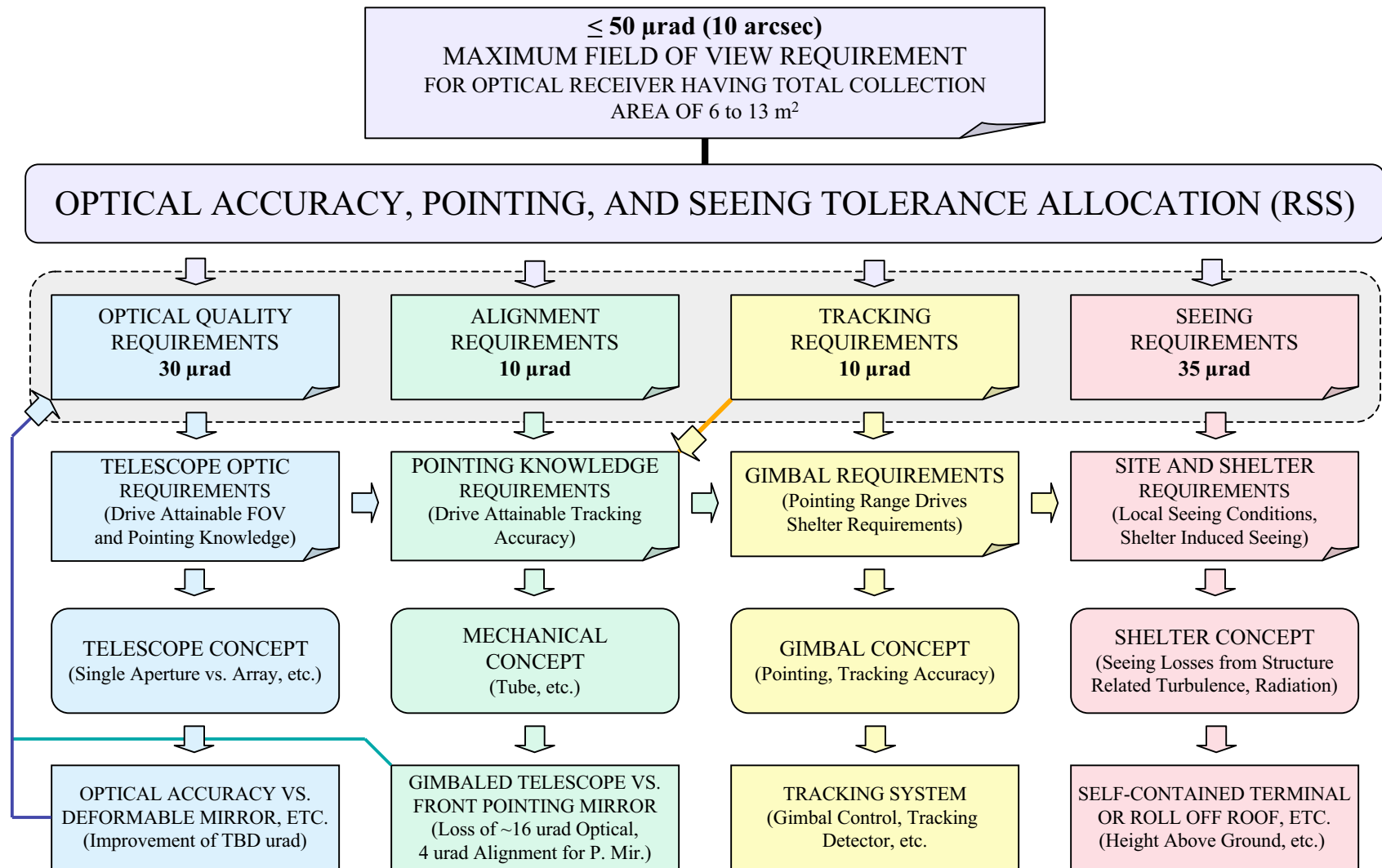
Photon Collectors vs. Astronomical Telescopes

Requirement	Astronomical Telescope	Photon-Collector for Lasercom
Image quality	Diffraction-limited	N/A $\leq 20X$ diffrac.-limit
Field-of-view	Large	Small
Operation	Night-time	Daytime & Night-time
Quantity	One of a kind	Multiple
Reliability	Moderate	High

Requirements

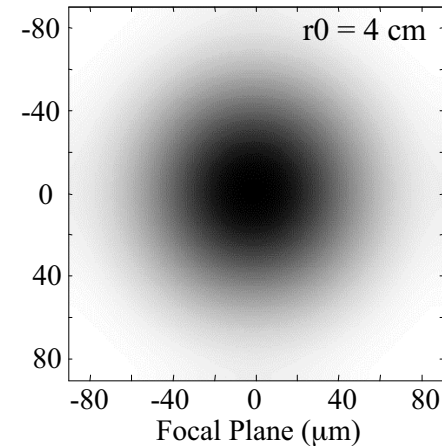
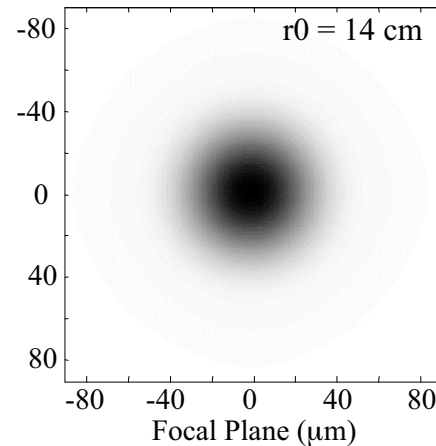
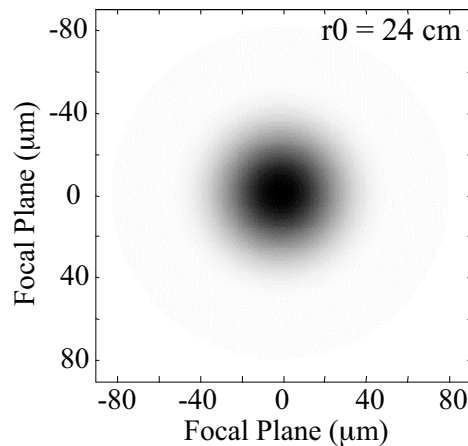
- | | |
|----------------------------|---|
| ➤ Transmit/Receive | Receive-Only |
| ➤ Wavelength | 0.8 to 1.6 μm |
| ➤ Equivalent aperture | 0.5 to 1 m diameter (for near-Earth)
10 m (minimum for deep space) |
| ➤ Telescope surface figure | < 20X diffraction-limit |
| ➤ Sky Coverage | Within 5° of the sun, goal 1° |
| ➤ Detection | Direct (incoherent) |
| ➤ Field-of-view | $\sim 50 \mu\text{rad}$ |
| ➤ Strehl | > 0.8 |
| ➤ Spot diameter | < 0.05 to 1 mm (higher w/ arrays) |
| ➤ Atmospheric seeing | 5-10 μrad (night-time)
25-100 μrad (daytime) |
| ➤ Tracking | Sidereal & HEO rates (for deep space) |
| ➤ Operation | Day & Night |

Flow of Optical Terminal Telescope Array Trades; Driving Requirements



Atmosphere's Contribution to Telescope Spot Size

Actual spot spread function size is driven by atmospheric turbulence (as quantified by the Fried parameter, r_0):



Assumptions:

No Adaptive Optics system

20 times diffraction limit telescope spot size = $104\mu\text{m}$ @ 1000nm

F/# 2 telescope with 3m focal length

Architecture Trades

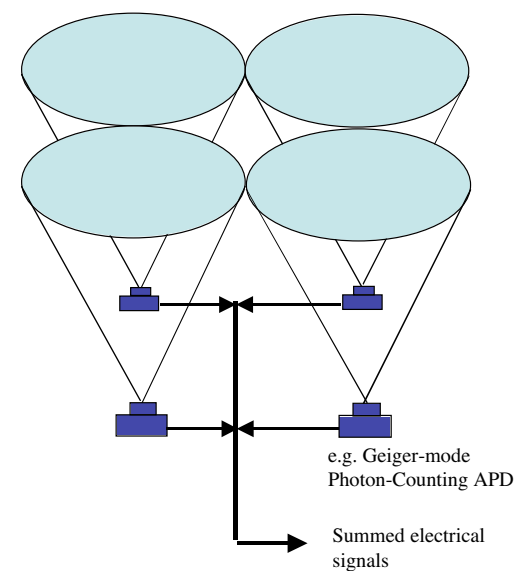
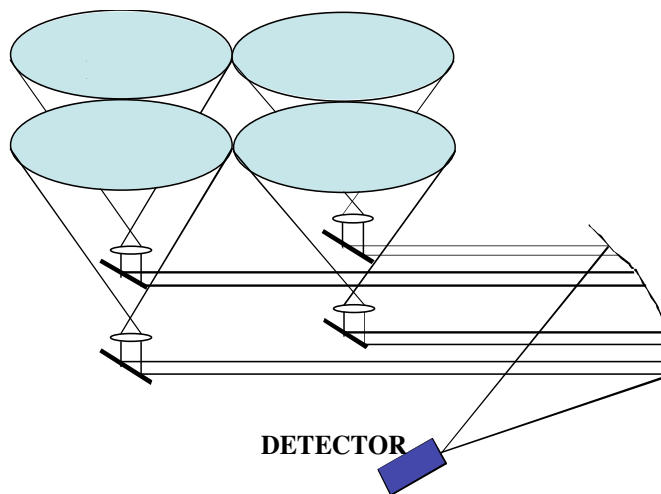
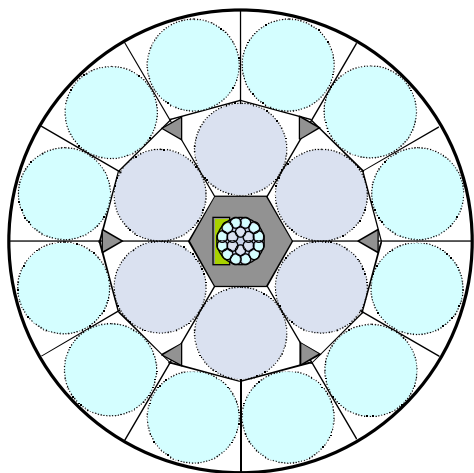
Viable options to identify lowest cost mirrors:

- Single monolithic large apertures
- Single segmented large apertures
- Array of 0.5 to 2.5-m diameter telescopes

Conclusions:

- An array of telescopes 1-m to 2-m in diameter meets the requirements and provides the lowest cost option.
- A spherical primary mirror along with a spherical aberrations corrector yields significantly lower cost
- A 200 X diffraction-limited (10 waves) mirror corrected to 20X diffraction limit (1 wave) also lowers costs significantly

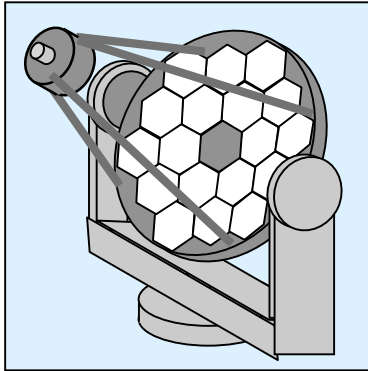
Architectures



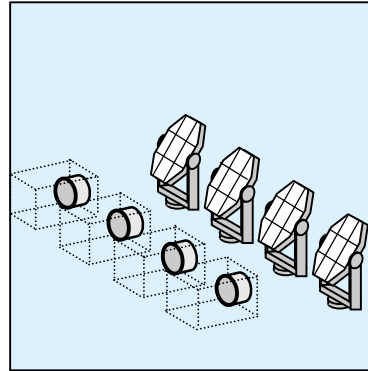
**Segmented
Primary mirror
Spherical
Hobby-Eberly
Telescope**



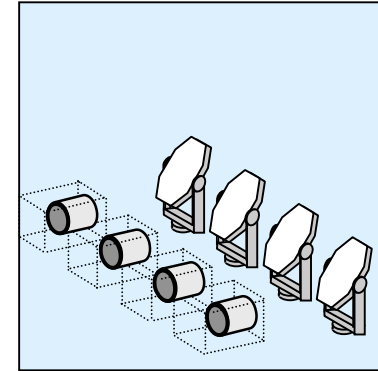
Concepts for Low Cost Optical Terminal



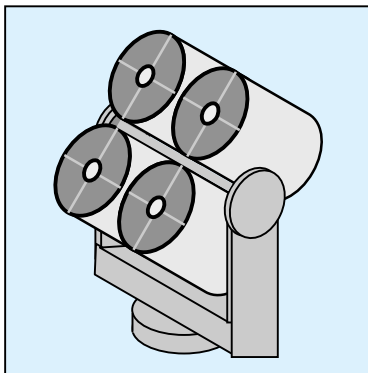
Single 3 meter aperture with eighteen 0.7 meter hexagonal mirror segments.



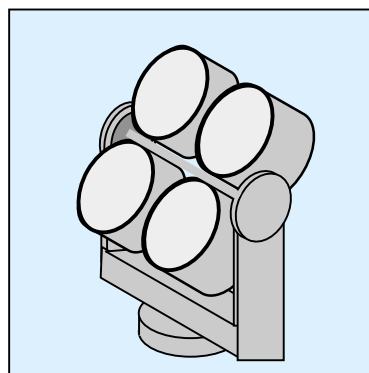
Array of 4 fixed 1.5 m telescopes, each with gimbaled 2.1 x 2.7 meter segmented pointing mirror.



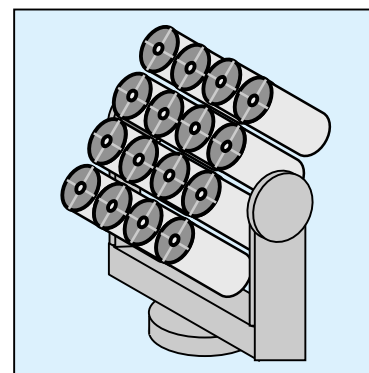
Array of 4 fixed 1.5 m telescopes or, each with gimbaled 2.1 x 2.7 meter composite pointing mirror.



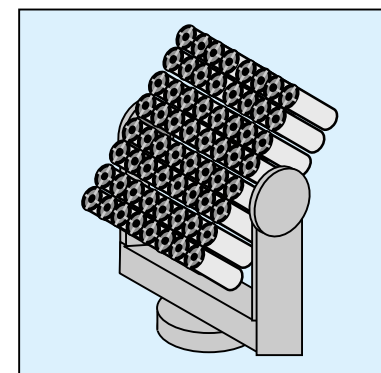
Array of 4 gimbaled 1.5 meter reflecting telescopes,



Array of 4 gimbaled 1.5 meter Fresnel lenses

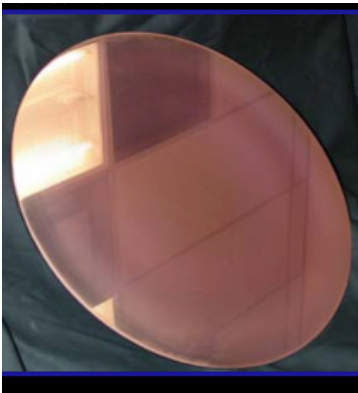


Sixteen 75 cm f/4 primary mirror segments,

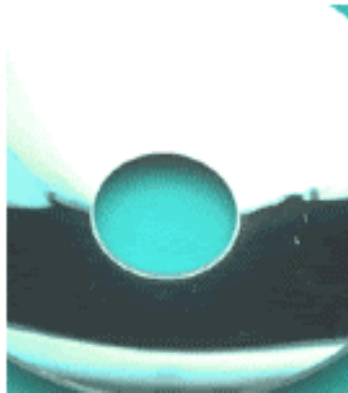


Sixty-four 37 cm f/4 primary mirror segments

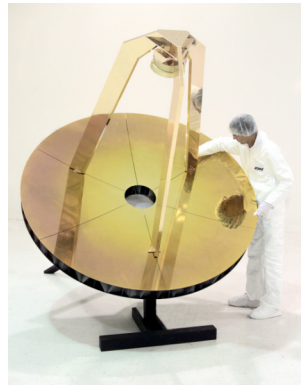
Potentially Low-Cost Large Optical Apertures



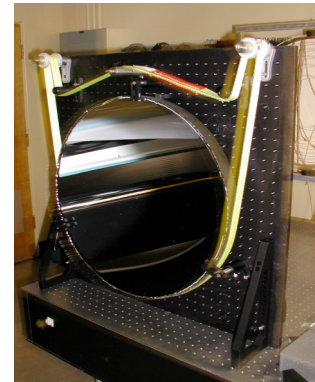
Nano-Laminate Mirror
(w/active surface correction)
1-m built (JPL/LLNL)



Replicated Mirror
Scalable to >5m
(commercial manufacturers)



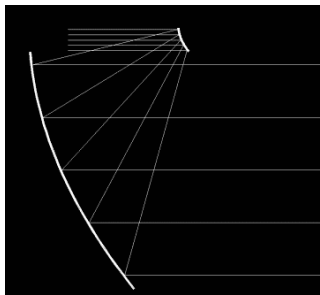
Composite Optics
Scalable to > 3.5 m
(COI)



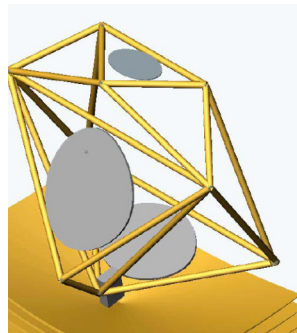
Spin-cast Polymer
Scalable to >10-m
U. of S. Carolina / JPL



Fresnel Lenses
5-m built



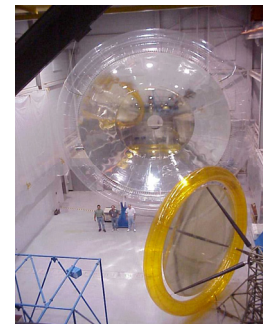
Cylindrical Primary Mirrors
Scalable to >25m (JPL R&D)



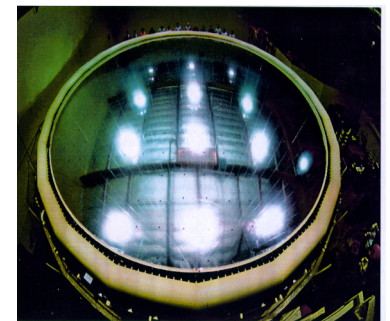
Dual Anamorphic Reflector
Scalable to >25m (JPL R&D)



Electro-formed
Scalable to multi-meter



Inflated Paraboloidal
5m and 10m Diameter
(SRS/AFRL)

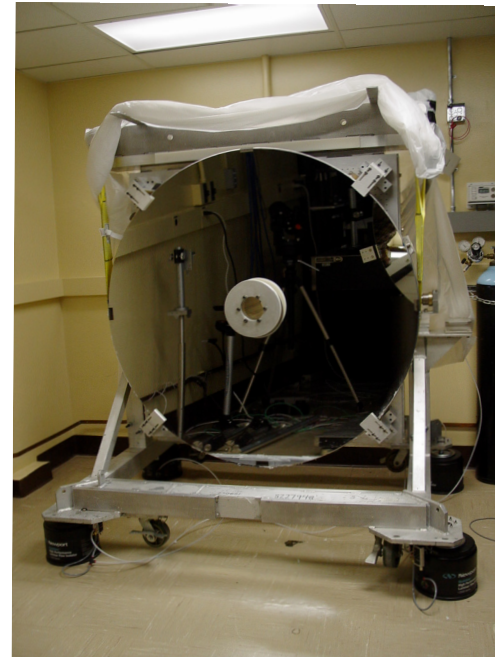


Parabolic Membrane Mirror
14-m Dia. built (AFRL)

Potentially Low-Cost Large Optical Apertures

JPL's current experimental approaches:

1. Spherical mirror slumped glass +
passive aberration corrector +
active optics compensator
2. Parabolic polymer mirror +
active optics compensator
1. Fresnel lens +
active optics compensator

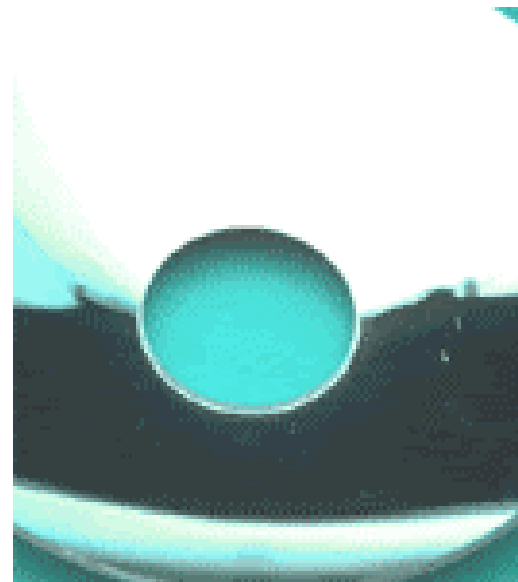


**1.5-m beam collimator
“Test Equipment”**

1.5-m Slumped Glass

1-m to 3.5-m replicated glass mirror

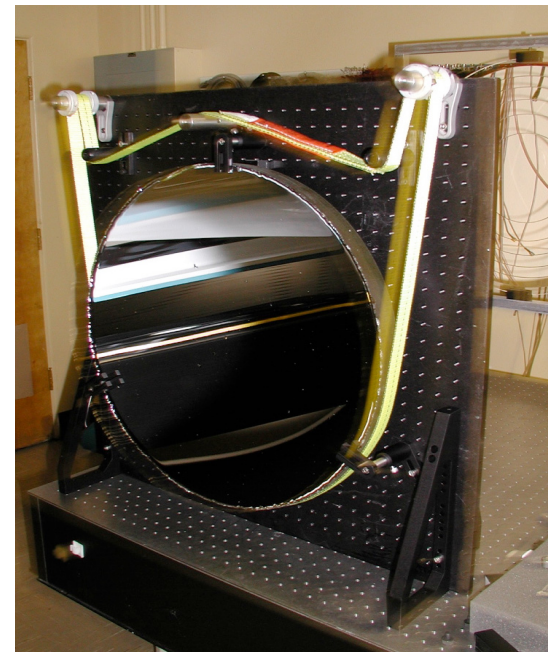
- Slumped glass technique utilizing a precision mold
- Both spherical and parabolic mirror are possible
- Minimal post polishing, surface quality 10-waves to > 100 waves (at $1\text{-}\mu\text{m}$)



Spin-Cast Polymer Mirror

1-m to 3.5-m spun-cast polymer mirror

- Spin-casting of polymers, multiple layers with decreasing thickness
- Spherical and off-axis spherical mirrors
- Fabrication time < 10 days
- No post polishing
- Surface quality 1-wave to ~100 waves
- 0.6-m fabricated at U. of S. Carolina.
Developing a 2-m version now under contract with JPL

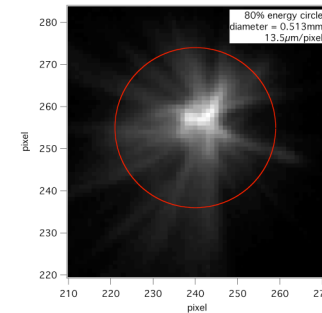
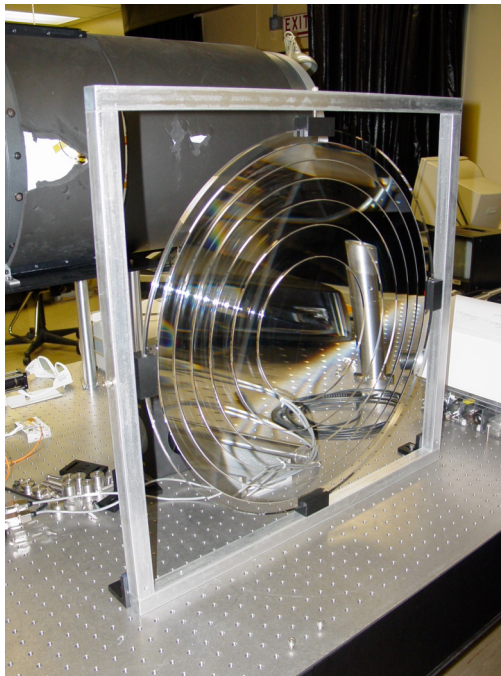


0.6-m Polymer Mirror

Large Diameter Diamond-Turned Fresnel Lenses

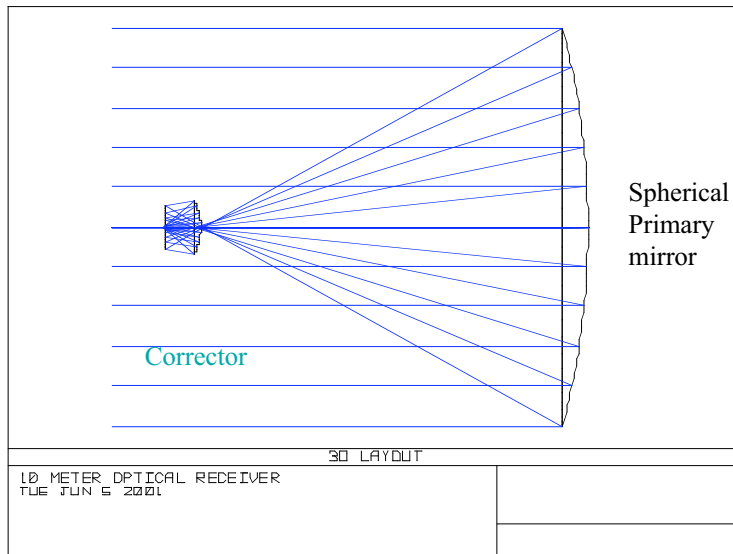
Multi-meter custom-made Fresnel lenses are promising, since

- Operation is at single wavelength (eliminates chromatic aberration)
- Field-of-view is very narrow (minimizes stray light)

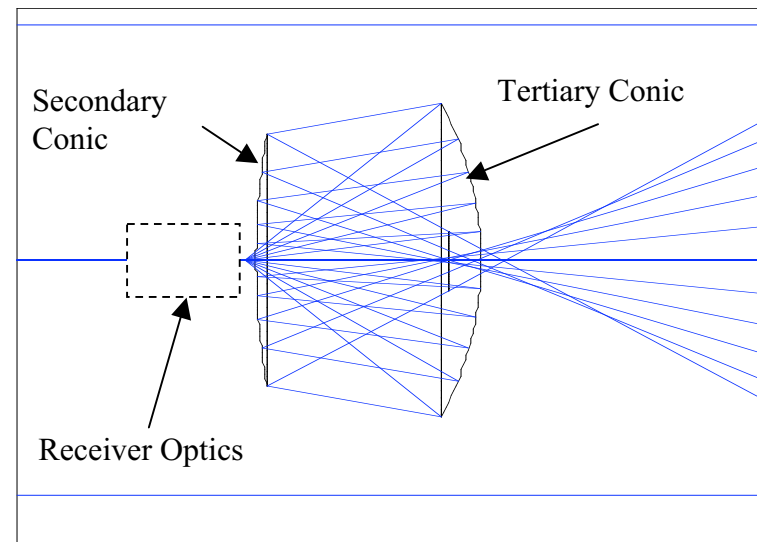


**ORA/JPL Designed, LLNL-diamond-turned
0.6-meter diameter Fresnel lens
Generates 0.51-mm spot size**

Spherical Aberration Corrector (for spherical mirror)



Telescope system using segmented spherical primary with corrector



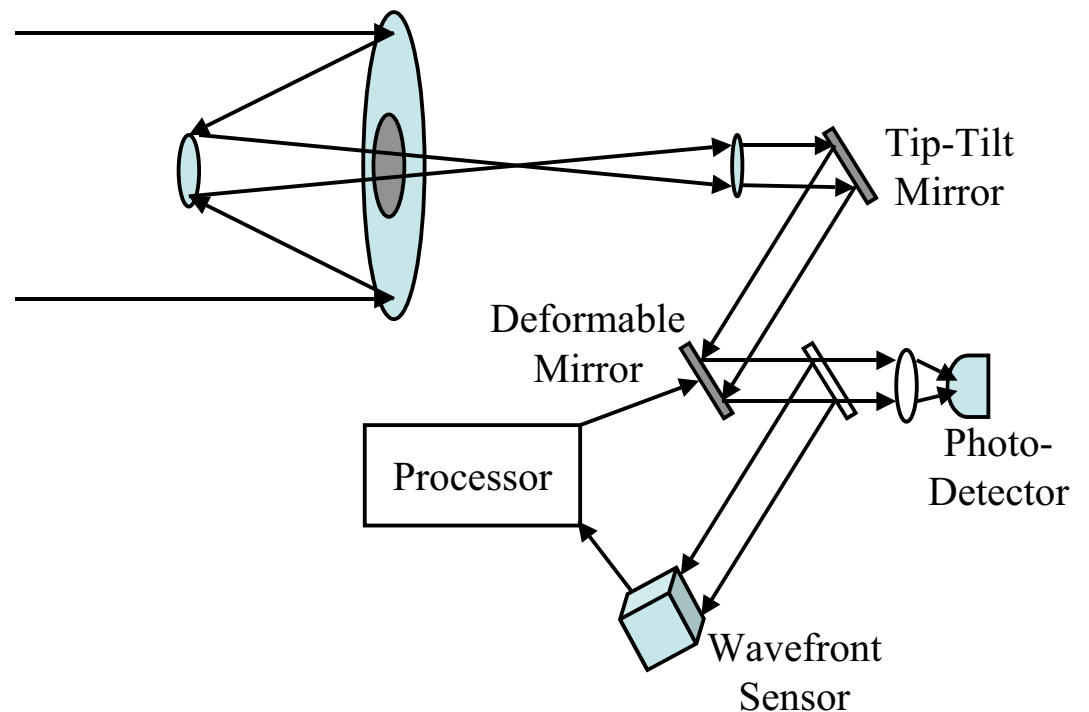
Expanded view of “clamshell” correction system

Surface Error Correction w/ Deformable Mirrors

“Active Optics Compensation”

Goal:

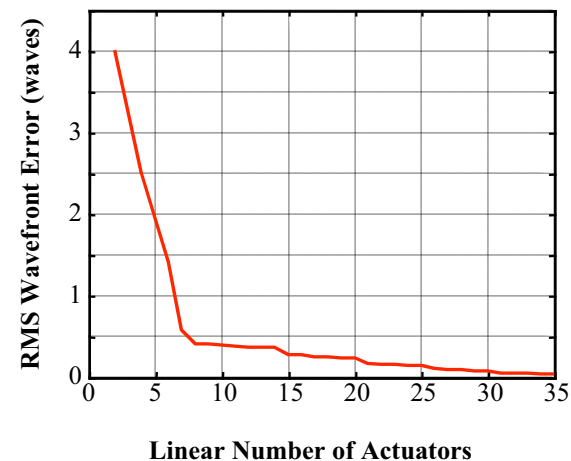
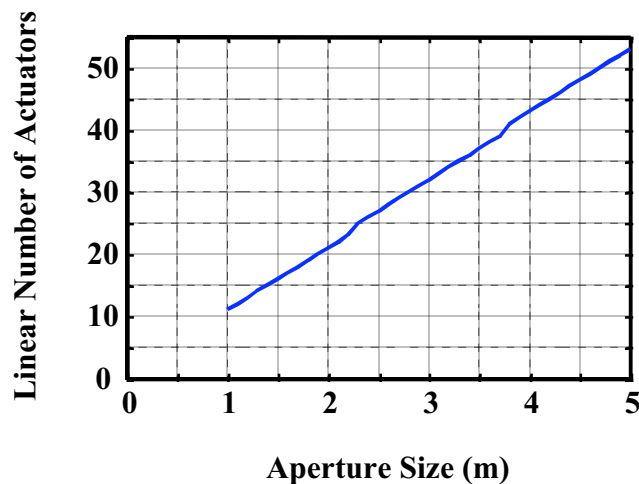
Reduce the slowly varying surface wavefront error of low-cost multi-meter-diameter mirrors from about 10 waves peak-to-valley, at 1 μm wavelength, to approximately 1-wave or less.



- Makes use of low-cost deformable mirrors
- Tip-tilt mirror added for the first order correction of atmosphere
- The wavefront sensor is being replaced with a simple focal plane or detector

The Required Number of Actuators

The required number of actuators is dictated by both the nature of aberration and aperture size.



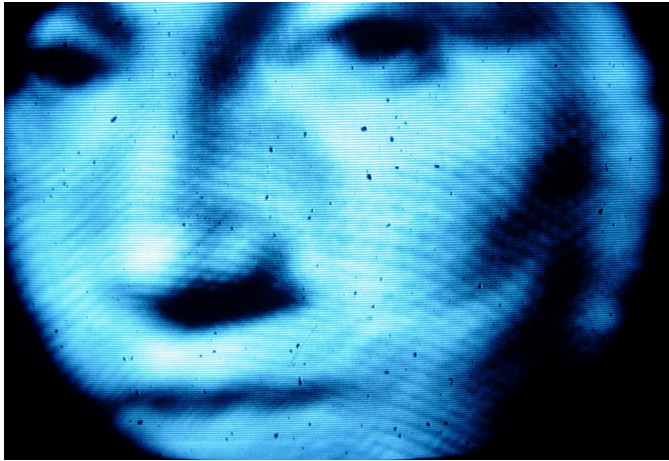
The required number of actuators for reducing RMS from 4 waves to 0.27 waves with telescope aperture diameters in the 1-5m range, assuming a fixed power spectrum.

Simulated for a 1.5m diameter mirror 20 linear actuators refer to a two-dimensional 20x20 element DM.

Wavefront quality improves with increased numbers of actuators

Experimental Results (with a 0.3-m Mirror)

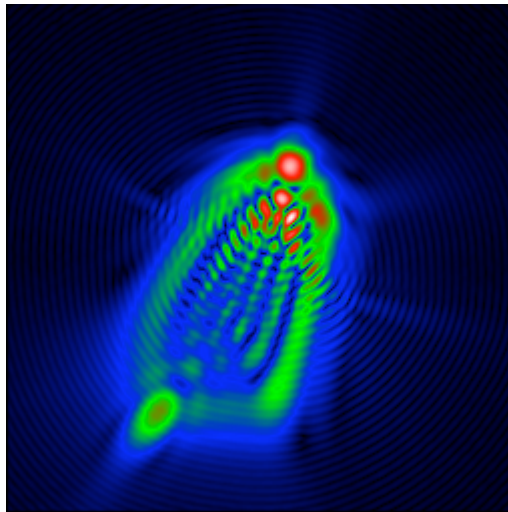
Before: 6.5 waves P-V at 633nm



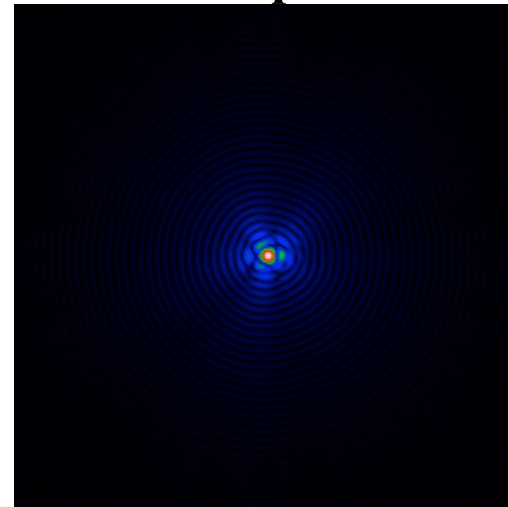
After: 0.26 P-V at 633nm



Before Compensation

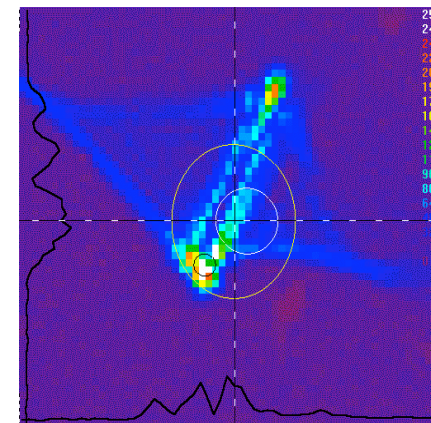
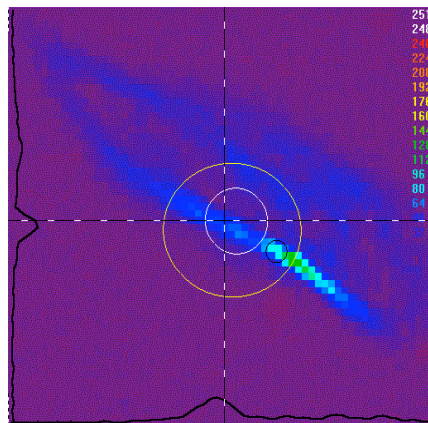
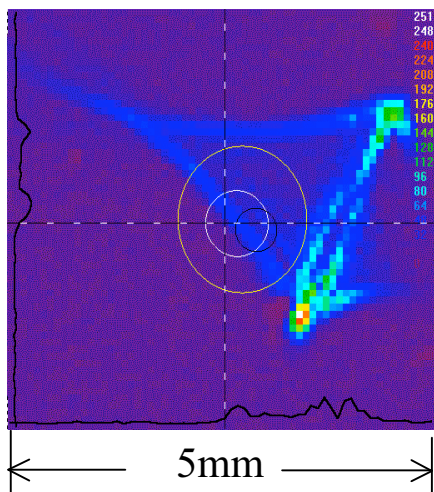


After Compensation

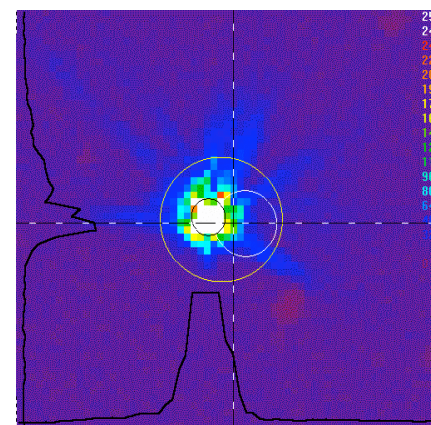
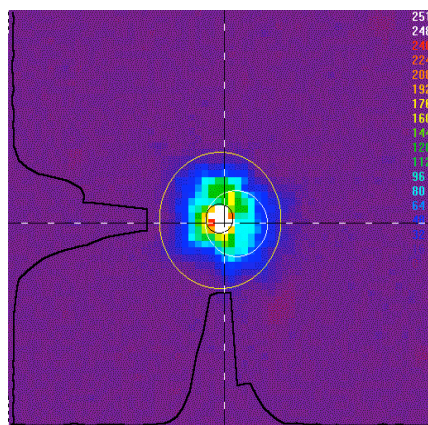
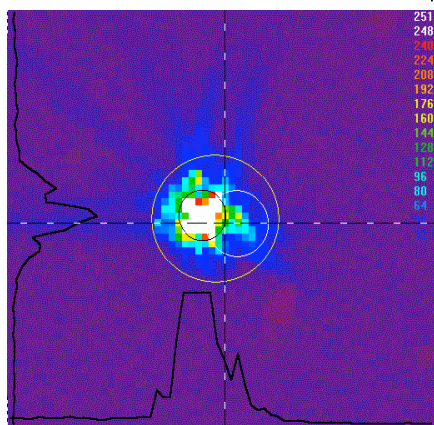


Example of Correction w/ Deformable Mirror

Before correction
8-10 waves of aberration (P-V)



After correction
0.2-0.25 waves of aberrations (P-V)

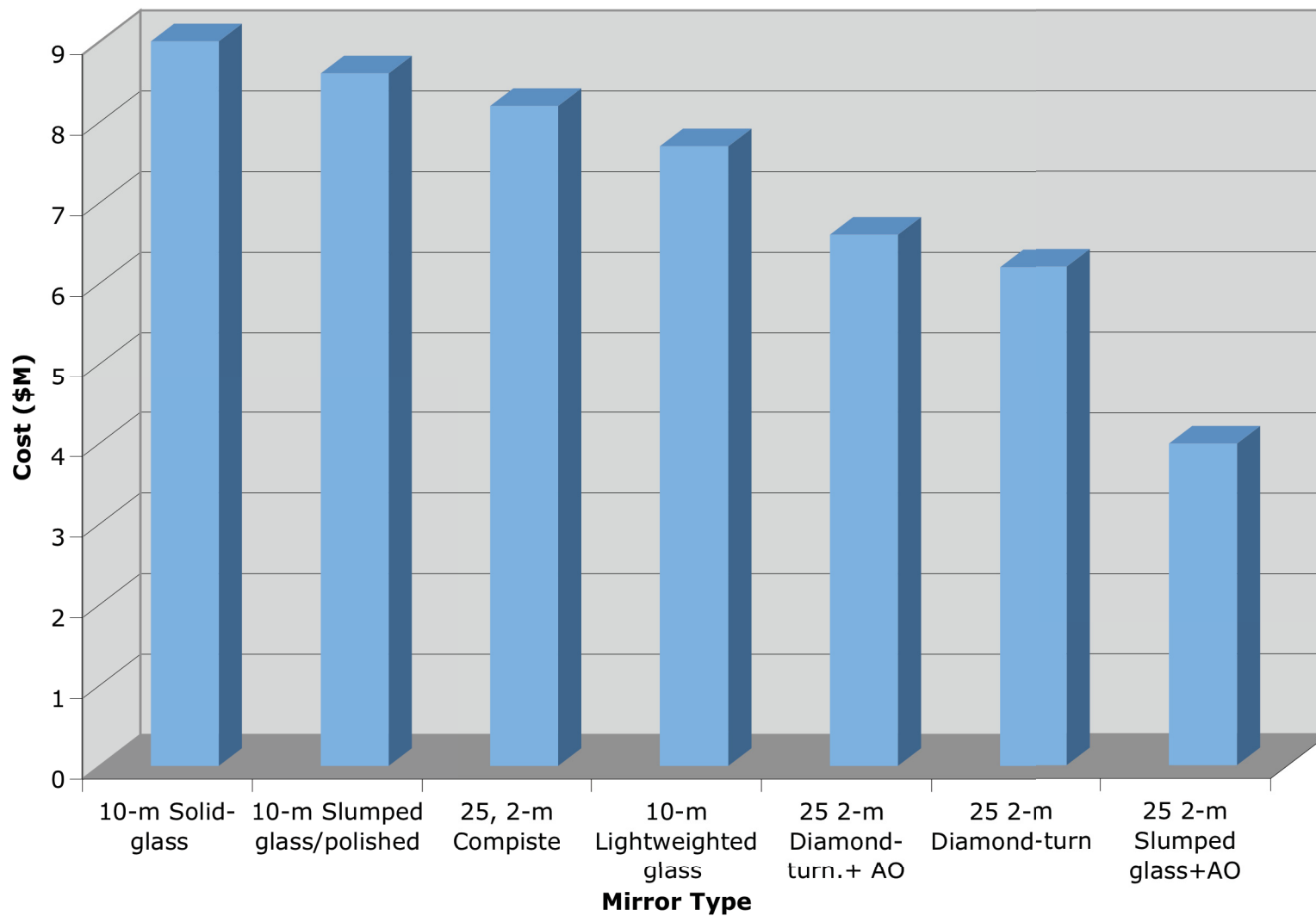


***Estimated Cost of Certain Telescope Options
for a 10-m Equivalent aperture***

Primary Mirror	Surface Figure (μ)	Primary Cost (\$M)	Mirror Support Cost (\$M)	Gimbal Cost (\$M)	Actuator Cost (\$M)	Total Cost (\$M)
10-m Solid-glass spherical panels	1	2	2	3	2	9
10-m Slumped glass spherical panels + polishing	2	1.6	2	3	2	8.6
Array of 25, 2-m Composite optics	2	5	1.2	2	0	8.2
10-m Lightweighted glass multiple-panel actuated	1	2.7	1	2	2	7.7
Array of 25 2-m Diamond-turned + active optics	1	3	1.2	2	0.4	6.6
Array of 25 2-m Diamond-turned mirror	6	3	1.2	2	0	6.2
Array of 25 2-m Slumped glass + active optics	1	0.4	1.2	2	0.4	4

Estimated Cost of 10m Spherical Collector Primary

Telescope Cost vs. Primary Mirror Type



Summary

Options for fabrication low-cost large-apertures for ground reception of optical communications where traded

Primary emphasis here is on the primary mirror

A slumped glass spherical mirror, along with passive secondary mirror corrector and active adaptive opticve corrector shoew promise as a low-cost alternative to large diameter monolithic apertures

To verify the technical performance and cost estimates, development of 1.5-meter telescope equipped with gimbal and dome, is underway